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THE INFLUENCE OF A FIRE-INDUCED CONVECTION COLUMN ON RADIOLOGICAL FALLOUT PATTERNS

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THE INFLUENCE OF A FIRE-INDUCED CONVECTION COLUMN ON RADIOLOGICAL FALLOUT

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The Experiment Station is maintained at Berkeley, California in cooperation with the University of California.

FOREWORD

This study serves as another illustration of how the diverse research requirements of two governmental agencies can be fulfilled in a single research program. The Forest Service, U. S. Department of Agriculture, as a result of its responsibilities in the control of forest fires, has considerable interest in studying the wind flows in and around fire-induced convection columns. Such flows markedly influence subsequent fire behavior. One way to study the wind flows aloft is through the introduction of some tracer material such as radiological fallout. Simultaneously, the Office of Civil and Defense Mobilization (OCDM) has an obvious interest in the effect of mass fires on the radiological fallout distribution pattern to be expected in case of nuclear attack. Answers to the two questions, one concerning fallout patterns the other concerning wind flows, can come from a single experiment. Indeed, from such experiments answers to either question would be meaningless unless the other were considered also. Thus, continuation of the program begun with this study under OCDM sponsorship would help answer some of the most pressing problems in radiological defense and at the same time be of application to those in the Forest Service whose responsibility is prediction of fire behavior on the basis of wind structure.

ABSTRACT

Since no nuclear devices have been detonated by the United States under conditions leading to both mass fires and radiological fallout, a theoretical and small-scale experimental study was undertaken to see if fire-induced convection columns could significantly affect fallout patterns. Experiments were conducted in a 6- by 6-foot low-velocity wind tunnel using full-scale fallout simulants. Values of characteristic parameters of fallout patterns were compared for experiments conducted with and without fire, all other factors being held constant. As predicted by theory, a fire upwind of the region of deposition introduced a further downwind movement and lateral dispersion of the fallout. In a few experiments in which the fire was located at the edge of the no-fire pattern, air flow into the convection column shifted the pattern peak upwind. These results suggest quite strongly that effects which can markedly alter civil defense planning will be found for large-scale fires. Since this effect can be significantly influenced by the air flow into and around the column, open air experiments on a larger scale should be performed so that such flow will not be affected by tunnel walls and ceiling.

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INTRODUCTION

IMPORTANCE OF THE STUDY

The detonation of a high-yield nuclear weapon at or near the surface of the earth results in damage which has been summarized in terms of four principal categories of effects: (1) blast, (2) thermal, (3) prompt radiation, and (4) fallout. The first two may act jointly in producing a mass fire which can extend the range of damage well beyond the extent of the primary prompt effects. The fourth results from the deposition of large quantities of highly radioactive particles produced in the detonation. Distributed by air currents, these particles return to earth as a result of the pull of gravity. Radiation from this fallout extends the range of damage of such a detonation hundreds of miles beyond the range of the other three effects and extends the time of significance to many days, or even months, after the time of detonation.

Previous studies of the transport of small, light materials such as pollen and mold spores have indicated that such small particles are greatly influenced by warm air currents such as those produced over an urban complex.[1/] Theoretical analyses of convection columns above large-scale fires indicate that updraft velocities resulting from even moderate rates of heat output exceed the terminal downward velocities of most radiological fallout particles. It would appear, then, that convection columns induced by fires set by the detonation or deliberately set after the detonation could have a marked effect on fallout patterns. Under conditions of sizeable civil defense activity, such columns could greatly alter the necessary civil defense planning and action.

No nuclear detonations by the United States have permitted observation of the interrelationships between (1) the mass fires which can result from such detonations and (2) the fallout of radioactive material following a surface or near-surface burst. Only two detonations are known to have occurred under conditions where mass fires could form. Both these detonations, at Hiroshima and at Nagasaki, were air bursts in which no fallout would be expected. All test devices detonated by the United States have been set off at sites where the principal surface area was sand or water, neither of which will support combustion. Consequently, the interrelationship between mass fires and fallout must be investigated theoretically and through the use of smaller-scale experiments.

1/ Heise, H. A., Meeting of the Southern Flying Physicians Association, Washington, D. C., November 13, 1956. (Reported by Associated Press.)

PAST WORK

Harwit (1956) reported the results of a study on the deposition of airborne particles on a large heated surface. This study considered cases of low heat output (of the order of micro calories per sq. cm. per sec.; for example, the natural heating of an urban area to a few degrees above the ambient temperature of the surroundings). From theoretical computations, Harwit estimated that heat outputs greater by at least a factor of a hundred, (producing upward velocities of the order of 100 cm. per sec. or more), would be needed to produce an appreciable effect on the particle deposition pattern.

Theoretical treatment of the convection above heat sources (Scesa & Sauer, 1954; Scesa, 1957) indicate, too, that when the heat output of the source is low with respect to the ambient winds, the effect of buoyancy may be neglected (no convection column will form). On the other hand, heat outputs which may be expected in fire situations similar to those in forest fires (of the order of kilo-calories per sq. cm. per sec.) are sufficient to permit the formation of a convection column in spite of the presence of moderately strong natural winds. In such convection columns the buoyancy effect produces updraft velocities of the order of thousands of cm. per sec. Since the terminal velocities of most fallout particles are expected to be lower than these values (Kellogg, et al., 1956), such columns should have a marked influence on the deposition pattern of such fallout particles. For fires started by the nuclear detonation itself, such influence may include:

1. Prevention of deposition in an area which might otherwise be expected to be highly radioactive.

2. Concentration of fallout in regions which might otherwise be relatively less radioactive.

3. Under certain circumstances, a gross change in the entire fallout pattern.

In addition, certain situations might lend themselves to the use of deliberately set fires as contamination prevention or decontamination tools.

In September of 1956, a series of preliminary experiments were performed to investigate the possibility of burning out the fuel to decontaminate a combustible area which had been exposed to radioactive fallout (Broido, 1957). Although the experiments were limited, the broad conclusions reached included the following: In areas with fuel content below 1 ton per acre, only a small degree of decontamination (less than 20%) could be expected. Fast-forming, rapidly burning fires in contaminated areas as small as 1/10 of an acre with fuel loading of 20 tons per acre can result in the removal of perhaps a third of the fallout, and the removed material is disbursed so that there is no significant concentration in any other region. The experiments indicated that under the much more severe conditions found in a large area mass fire, more striking effects might well occur.

Shipley (1958) published the results of a brief study on the dispersal of fallout by means of a heat source. His theoretical analysis included a procedure which admittedly was "arbitrary and had no theoretical or experimental basis for being correct." His experimental technique was to measure the number of particles of chalk dust falling on slides set under and near an electrically heated wire grid mounted in a small office room. In these experiments the chalk dust was observed to be lifted as it passed over the heat source area. However, a count of the fallout deposited on and around the area revealed only a small decrease in the amount of material deposited. The author points out that these unfavorable results may have been the fault of confining the experiment to a small room. He states: "Had the experiments been conducted in a much larger area it may be that fallout dissipated from the heat sources could have been carried further away from the protected area and there deposited."

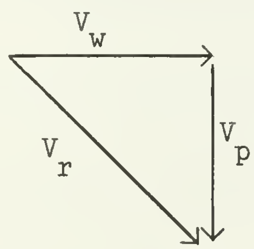
SCOPE OF THE PRESENT STUDY

A preliminary analytical evaluation of the problem indicated that no true small-scale modelling was feasible. However, the availability of a 6- by 6-foot low velocity wind tunnel which permitted the introduction of fires giving appropriate updraft velocities made it appear that full-scale particles having distribution as actually observed in fallout might give results of considerable interest.

THEORETICAL

EFFECT OF AN IDEALIZED CONVECTION COLUMN ON THE FALL OF A SINGLE PARTICLE

Assume a particle at point A in figure 1, a distance H_o above ground in an idealized homogeneous atmosphere of constant density, falling with a terminal velocity V_p in a wind of constant velocity V_w. The vector diagram is simply:



and the particle would fall along the path AR in figure 1, landing at point R , a distance L_o downwind of point A. The time of fall would be H_o/V_p , and so

$$L_o = V_w t = \frac{V_w H_o}{V_p} \qquad (1)$$

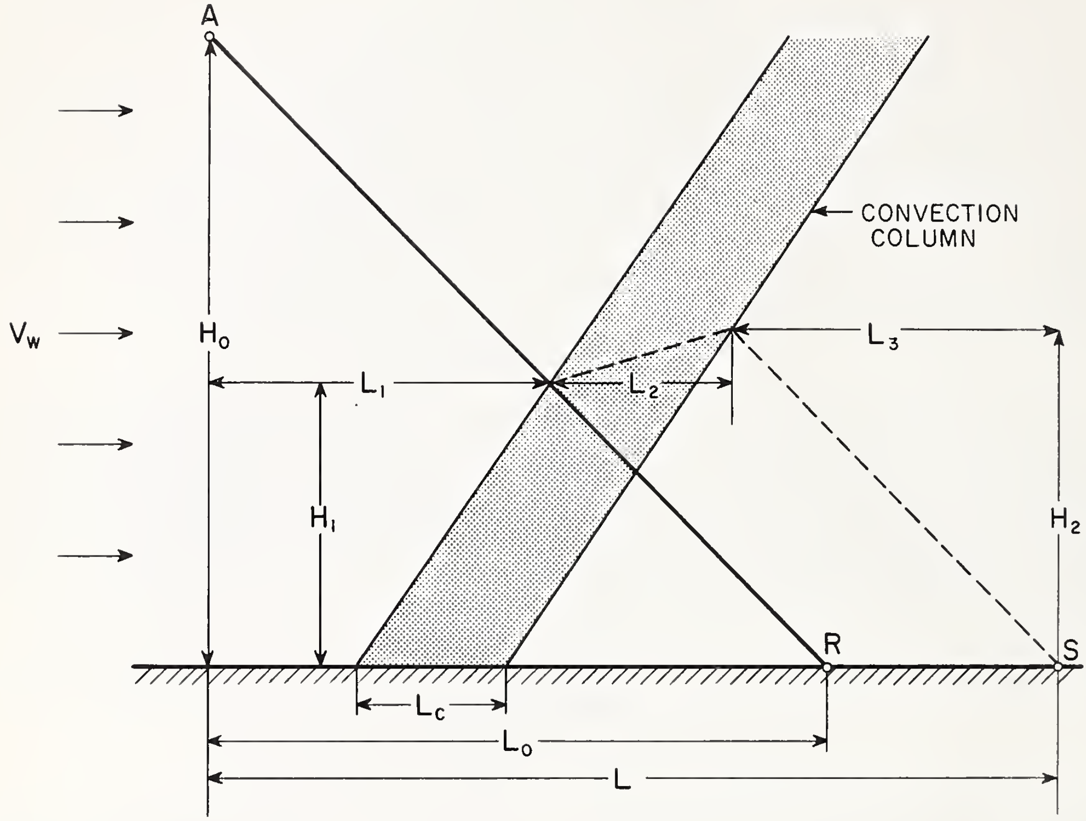
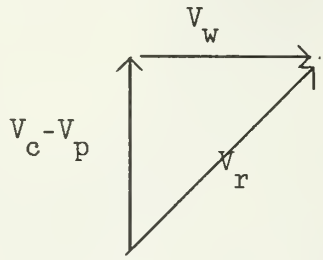


Figure 1.--Fall of a single particle through an idealized convection column.

Now, assume an idealized convection column is introduced into the system. This convection column is produced by a source generating air of the same physical properties as the surroundings (temperature, pressure, etc.) and pumping this air upwards at a velocity V_c . This column of air rises at an angle dependent upon V_c and V_w and is then fed into a sink. A slip surface is assumed to exist at the column boundary, so that the presence of the column introduces no circulation in the existing atmosphere. Thus, the trajectory of the particle would not change until it reached the leading edge of the column (at a height H_1). At this point the vertical velocity of the particle with respect to the ground becomes $V_p - V_c$. If $V_p > V_c$, the particle would continue to fall, but more slowly. If $V_p = V_c$, the particle would move through the column in a horizontal path with velocity V_w . If $V_p < V_c$, the particle would rise as it moved through the column in a path determined by the vector diagram:



and shown as the dashed line within the column in figure 1. When the particle reached the downwind edge of the column, it would again fall at the same angle as before (following the dashed line in figure 1) and land at point S . The downwind distance of fall, L , can be obtained by computing L_1 , L_2 , and L_3 and summing them.

As before, L_1 and L_3 are given simply as

$$L_1 = \frac{V_w(H_o-H_1)}{V_p} \quad \text{and} \quad L_3 = \frac{V_w H_2}{V_p}$$

In a similar manner, two expressions may be found for L_2 :

$$L_2 = \frac{V_w(H_2-H_1)}{V_c-V_p} \quad \text{and} \quad L_2 = L_c + \frac{V_w(H_2-H_1)}{V_c}$$

The displacement of the particles caused by the convection column, $\Delta L = L - L_o$, may be obtained from the above equations as

$$\Delta L = L_1 + L_2 + L_3 - L_o = L_c \left(\frac{V_c}{V_p}\right)^2 \tag{2}$$

Thus, the displacement of the particle by such an idealized convection column is seen to be completely independent of the wind velocity, being simply a function of the column width and updraft velocity and the fall velocity of the particle.

If the physical characteristics of the column are allowed to change (e.g., heated air), the fall velocity, with respect to the column gases, of the particle within the column is not the same as that outside the column. In this case, the displacement of the particle becomes:

$$\Delta L = L_c \left[\frac{V_c^2 + V_c(V_p - V_p')}{V_p V_p'} \right] \tag{3}$$

where V_p' is the terminal velocity of the particle in the medium of the column.

THE EFFECT OF AN IDEALIZED CONVECTION COLUMN ON AN EXTENDED SOURCE OF FALLOUT PARTICLES

Line Source of Particles

Consider the fallout particles in the previous example to be one of a large number of identical particles lined up in the same horizontal plane (fig. 2). In falling from height H_0 to H_1 these particles would follow parallel paths uninfluenced by the existence of the convection column shown in figure 2. At height H_1 the particle at A' enters the convection column and, following the path indicated by the broken line, ultimately lands at point S (rather than at point R where it would land had no convection column been present). The following particles enter the column at progressively later times and at lower elevations. Upon entering the column they follow a path parallel to that taken by the first particle and their points of deposition are displaced accordingly. Thus, the particle at B' when the first particle entered the column enters upon reaching point M and is displaced to land at point R . A particle starting its fall at point C would enter the column at its base (point P) and like the previous particles be displaced, so as to land at point Q . The particle at D , however, and all subsequent particles, would follow a straight-line path directly to the ground-landing in exactly the same position whether or not the column were present.

Thus, without a column the line of particles, EA , would land in a line of equal length, NR , on the ground. The presence of the column does not in any way change the length of this line, but it does break it into two segments, NO and QS .

The effect of the convection column on the accumulation of fallout particles on the ground in such a case, then, is dependent upon the point under consideration. Between points N and O no change occurs, that is, the same particles land at exactly the same points. From P

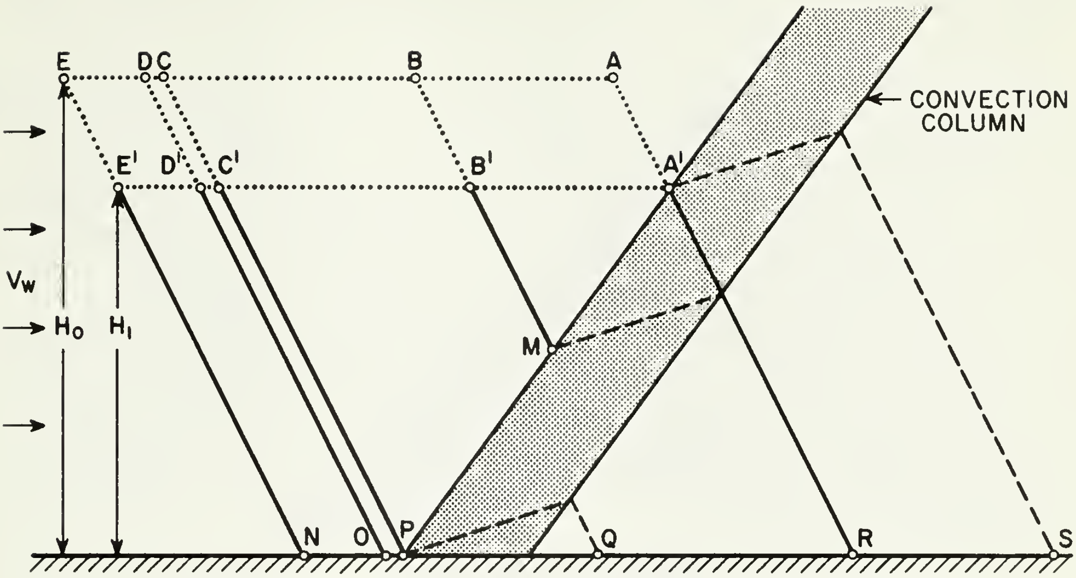


Figure 2.--Fall of an extended source of identical particles.

to Q fallout particles which would arrive without a convection column are totally displaced and no particles land in this region. From Q to R , although a displacement occurs, the particle which would normally land in this region is replaced by another identical particle and, thus, no change is observed. From R to S , particles now land where, without a convection column, no particles would have been found.

The previous paragraph illustrates the effect of such an idealized convection column on a line of particles which are identical in size and fall velocity. Consider, now, another such line of smaller particles located at such a position that, with their particular fall trajectory, they, too, would land in the region NR if no column were present. The effect of the convection column would be qualitatively the same as that given in the previous paragraph, but these smaller particles would be displaced a greater distance by the column. The degree of overlap of the downwind segments would be a function of the terminal velocity of the convection column. If, then, a large number of different sized particles were to be displaced by such an idealized column, the over-all result in the downwind region would be an increase in the size of the region on which fallout would land, with a corresponding decrease in concentration at any one point.

Cloud of Particles

The extension of the argument to a 3-dimensional cloud of particles is straightforward. Consider, for example, the area EAA'E' in figure 2 to represent a cross-sectional slice through an idealized cloud of identical particles. Without a convection column all of the particles in the line AA' would land at point R . Those in the line EE' would land at point N . Under the influence of the idealized convection column, all of the particles in the line AA' now land at point S . However, the particles in the line BB' now land at point R in place of those which have been displaced. Thus, assuming a uniform concentration through the cloud, if the lines BB' and AA' are equal in length, no change will occur in the concentration of particles landing at point R . Similarly, for this example, the effects at any other point on the ground follow directly from what has already been said about the line source.

This example, however, has considerably idealized the true situation by assuming the cloud to have constant horizontal upper and lower boundaries and side boundaries with slopes identical to the fall trajectory of the particles. Consideration of the real dimensions of a fallout cloud as well as expected wind velocities and fall velocities of the particles would indicate that a more reasonable picture is that given in figure 3. The wind velocities are, in general, expected to be considerably greater than the fall velocities of the particle, and thus the trajectory would be more nearly horizontal. In such cases, the line through the cloud of particles which would land at a given point on the ground would terminate at the upwind edge rather than the upper edge of the cloud. A downwind shift of this cloud, then, would result in a shortening of such a line and a decrease in concentration of particles at a point. Thus, the introduction

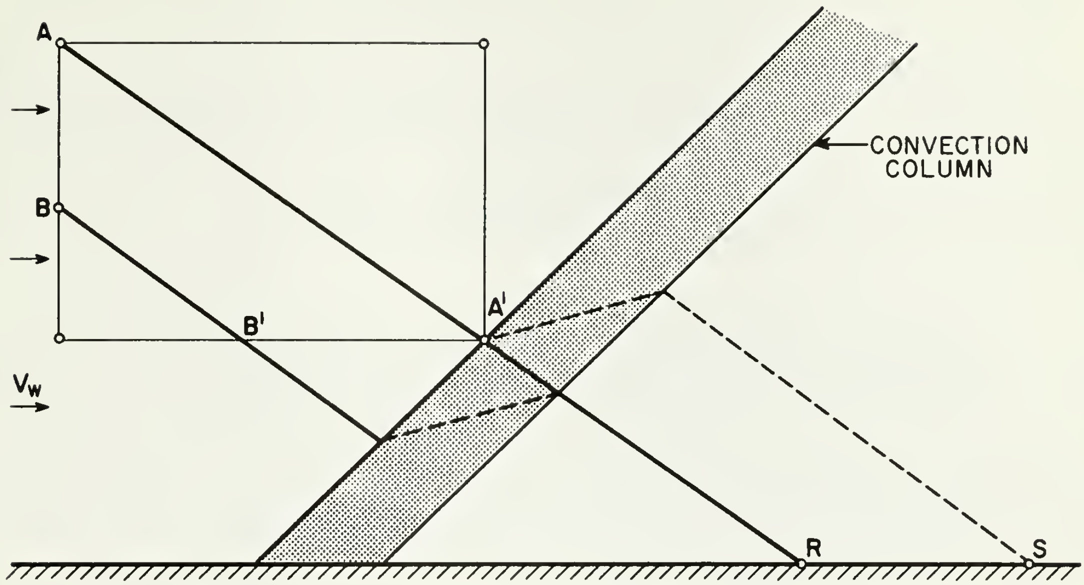


Figure 3.--Expected fall trajectory under probable wind conditions.

of the convection column shown in figure 3 would result in the particles in the line BB' landing at the point which otherwise would be occupied by those in the line AA' . Since BB' is just half the length of AA' , the concentration of particles of this size landing at point R would be cut in half.2/

THE EFFECT OF A REAL CONVECTION COLUMN

The factors which have been considered up to this point are those which influence the fall of the particles within the convection column itself. In the idealized example considered, no other effects could occur since the gases of the convection column were generated and dispelled without being circulated into the surrounding atmosphere. In a real convection column, such circulation must be taken into account.

Although some gases are produced in a combustion reaction, much of the gas rising in a fire-induced convection column is air entering the column at various elevations above grade. The rising gases do not terminate at some sink, but recirculate and influence the general flow of air in a large area around the column itself. Corcos (1958) has shown that particles of the type considered here follow quite closely the circulation patterns of the atmosphere. Thus, before the total effect of a convection column on a fallout pattern can be ascertained, the flow of air around the convection column must be understood.

Unfortunately, practically no information is available about such flow. Strong indrafts have been measured at the base of a fire-induced column, but little is known about such questions as: What fraction of the air entering the column enters at the base and what fraction at higher elevations? What fraction enters downward of the fire and what fraction upwind or crosswind? When the rising air "spills over" at the top of the column, how far does it travel at these upper elevations before recycling at elevations near the ground? Until more is learned about answers to questions of this type, little more can be ascertained theoretically about the influence of a real convection column on a fallout pattern. In fact, it is to be hoped that experimental studies of such influences may help provide additional insight into these air flows.

EXPERIMENTAL

FALLOUT SIMULANT

When a nuclear weapon is detonated on or near the surface, great masses of pulverized debris are sucked upward from the surface and are mixed with radioactive fission products released by the explosion. The composition of this fallout depends, of course, upon the composition of the surface over which the detonation took place. The fallout particles vary considerably in shape and in size. Consequently, the rate of descent of fallout ranges from the "throw-out," the rapid deposition of

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2/ A somewhat different treatment is given by Corcos (1958), who considers the concentration gradient of particles in a non-uniform cloud. Application of this treatment to the discontinuous cloud considered here would give identical results if the concentration gradient were taken as that over a line the length AA' extended through the points BB' and on beyond the cloud.

large-sized material in the vicinity of the crater, to the slow rate of descent of the smallest particles which circle the earth many times. This study dealt with the intermediate range of particle sizes, namely, those that would be expected beyond the region of total primary destruction, but whose concentration would be sufficiently high to create a severe radiological hazard. Specifically, attention was focused on particles in the 100- to 300-micron range.

Choice of Simulant

Three principal factors influenced the selection of a simulant to this fallout material:

1. Theoretical computation (see, for example, Corcos, (1958), indicated that a true scaling experiment was not feasible.

2. The use of very much lighter particles would introduce the possibility of other complicating effects and make extrapolation more questionable.

3. The U. S. Naval Radiological Defense Laboratory (U.S.N.R.D.L.) was using, and had available, a simulant of appropriate composition, density, and shape and size distribution. This material, also used in the earlier decontamination experiments (Broido, 1957), consisted of soil taken from the test site at Camp Stoneman, California and dried, pulverized, and sieved until it passed a No. 30 mesh screen.

To simplify interpretation of the results, this material was further subdivided by sieving through a series of Tyler Standard Screens. In this procedure, very little material was found of size large enough to be held by a 250-μ screen, and the sieving procedure became too slow to be practical for sieve sizes smaller than 74-μ. Since this smaller material settled too slowly to be used within the confines of the wind tunnel available, no further breakdown was attempted.

The fallout material used, then, consisted of five fractions of material not held by a 250-μ screen and held, respectively, by 210-μ, 177-μ, 149-μ, 105-μ, and 74-μ screens.

Method of Measuring

An appropriate method for determining, or even defining, the "size" of an irregularly-shaped particle is subject to considerable arbitrariness. Thus, a sieve with square holes of side "ℓ" in length will pass spherical particles of diameter up to length "ℓ." On the other hand, a particle in the form of a square plate can, in principle, pass through such a hole if

the length of the edge of the plate is less than $\sqrt{2}\,\ell$. Measured under a microscope, then, at least some dimensions of an irregularly-shaped particle passing through a 250-μ screen would be larger than 250-μ.

Even if all of the dimensions of an irregularly-shaped particle were accurately known, the definition of the particle "diameter" would be subject to considerable ambiguity (Cadle, 1955). Statistical diameters, based upon measuring the dimensions of a large number of particles, are usually used. If the length, breadth, and thickness of the particle can be estimated, the arithmetic average of the three diameters may be used. Alternatively, the diameter of a sphere (or the length of the side of a cube) of equal volume may be defined as the particle diameter. A useful definition of diameter of particles measured under a microscope was proposed by Martin (1924). It is the distance between opposite sides of the particle measured crosswise of the particles and on a line bisecting the projected area. Since irregularly-shaped particles will generally land "flat," that is, with their smallest dimensions perpendicular to the surface on which they land, this measurement will not give a good indication of the smallest dimension. However, if a sufficiently large number of particles are measured, a good average value of the other two dimensions of the particle will result.

In the course of these experiments selected samples were collected on gummed transparent paper. After a preliminary statistical analysis established that these particles were randomly distributed throughout the paper, mean Martin's diameters were obtained by dividing the paper into a large number of small squares and selecting the squares for measurement from a table of random numbers. These diameters were then compared with the gross values obtained using the sieving technique.

Since, for purposes of these experiments, the particle property of prime interest is the fall velocity of the particle, an experiment was performed to establish an "effective diameter." A vertical wind tunnel, to be described in a subsequent report, was designed and built (fig. 4). Fallout particles were then mixed with spherical glass beads (fig. 5) of appropriate size. The mixture was fractionated in the vertical wind tunnel and the various fractions measured under the microscope (fig. 6). The diameter of the glass beads in a given fraction established the fall velocity of the entire fraction. The Martin's diameter of the fallout could then be related to this effective diameter.

Table 1 gives some representative results of such a separation. For these experiments, a gross sieve-size sample was fed into the hopper of the vertical wind tunnel. Each such sample was then fractionated by progressively lowering the voltage to the wind tunnel exhaust blower in 5 volt increments and collecting the material falling out of the tunnel.

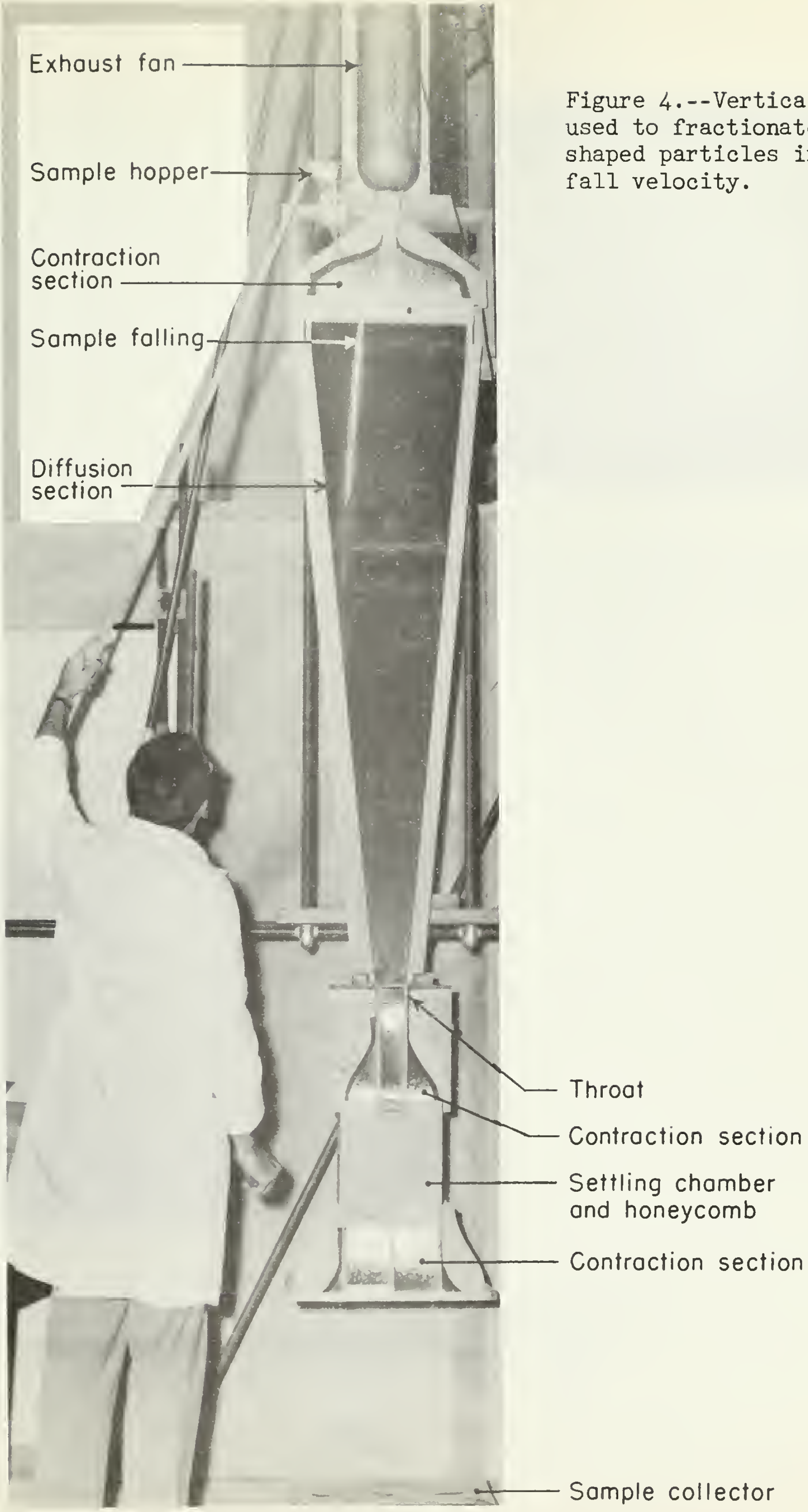

Figure 4.--Vertical wind tunnel used to fractionate irregularly shaped particles in terms of fall velocity.

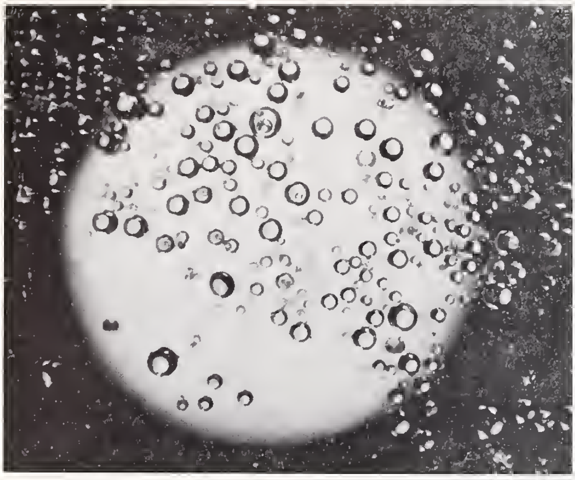

Figure 5.--Mixture of glass beads added to fallout particles prior to separation.

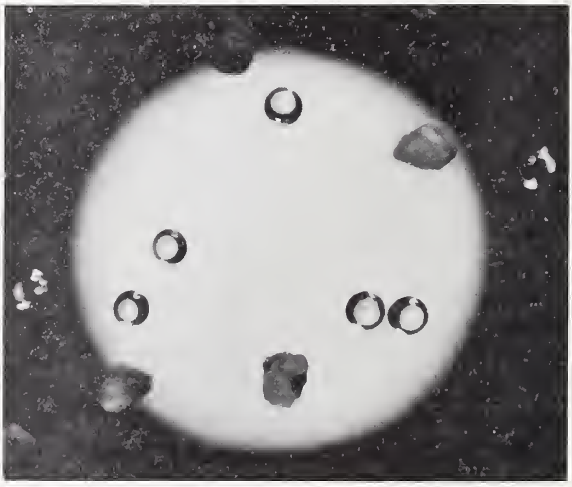

Figure 6.--Typical sample of fractionated material. Constant size of glass beads establishes fall velocity of irregularly shaped fallout particles.

Table 1.--Representative results of particle size fractionation in terms of fall velocity

Sieve size, microns	Fraction number	Glass spheres (Density = 4.23)		Computed fall velocity	Fallout particles (Density = 2.50)	
		Mean diameter	Standard deviation of sphere sizes		Mean diameter	Standard deviation of particle sizes
		Microns	Microns	Ft./sec.	Microns	Microns
74-105	2	91.5	11	2.5	104	19
	5	78.5	9	1.9	99	16
200-250	1	214.2	17	7.3	326.5	43
	11	151.2	4	4.9	256.6	55

Method of Dispersing

Mathematical fallout models used to predict the distribution of fallout on the ground after a nuclear detonation generally begin with a fallout cloud stabilized at its maximum elevation. The models then attempt to predict the motion of the particles constituting this cloud as a result of the pull of gravity and the influence of the wind. Such models eliminate the complicating features introduced by the detonation itself and by other parameters important during the formative stages of the cloud. Similarly, these experimental studies attempted to produce a cloud which would have stabilized and which would be moving only as a result of the influences of gravity and the wind at the time the particles entered a convection column. The ideal experimental cloud would be completely uniform, particularly in its crosswind dimension, and would be wider than the convection column used. In addition, the concentration of particles would not be sufficient to influence the physical characteristics of the air through which they fell, but would be sufficiently great to give a readily measurable pattern.

The simplest method of injecting the fallout particles into the wind tunnel airstream would be to drop the sample from a funnel. This, however, would produce an undesirably narrow pattern. Dropping from a hopper oriented lengthwise across the tunnel was ruled out because of the inability of getting a uniform flow from such a hopper. The various devices used by the U.S.N.R.D.L. to spread contaminant in their decontamination studies were examined, and the only one which showed promise for these experiments, a De Vilbiss Powder Blower, Model 175, was tried. However, this device proved to be too small to produce a sufficiently large cloud of material.

The disperser finally selected was a Binks Model No. 171 Flock Gun (fig. 7). This compressed-air-powered spray gun was designed to handle particulate matter mixed with paints. The metal can that came with the gun was removed and the gun was adapted to operate with the sample contained in a one-quart glass jar. A series of experiments were performed to investigate the effect of air pressure, level of fallout in the jar, gun nozzle setting, and duration of firing on the shape and consistency of the pattern. Examination of the data indicated that the most satisfactory results were obtained with the jar filled to one-third to two-thirds capacity, with the air pressure at 30 psig for a 10-second run, and with the gun nozzle adjusted to give a wide, flat horizontal cloud.

Although the carefully controlled conditions led to a fairly reproducible fallout pattern, the total quantity of material discharged from the gun in a run of fixed time duration varied by as much as a factor of 5 for successive runs. Thus, for all experiments, the general shape of the distribution, rather than the total amount of material leaving the gun, was of significance.

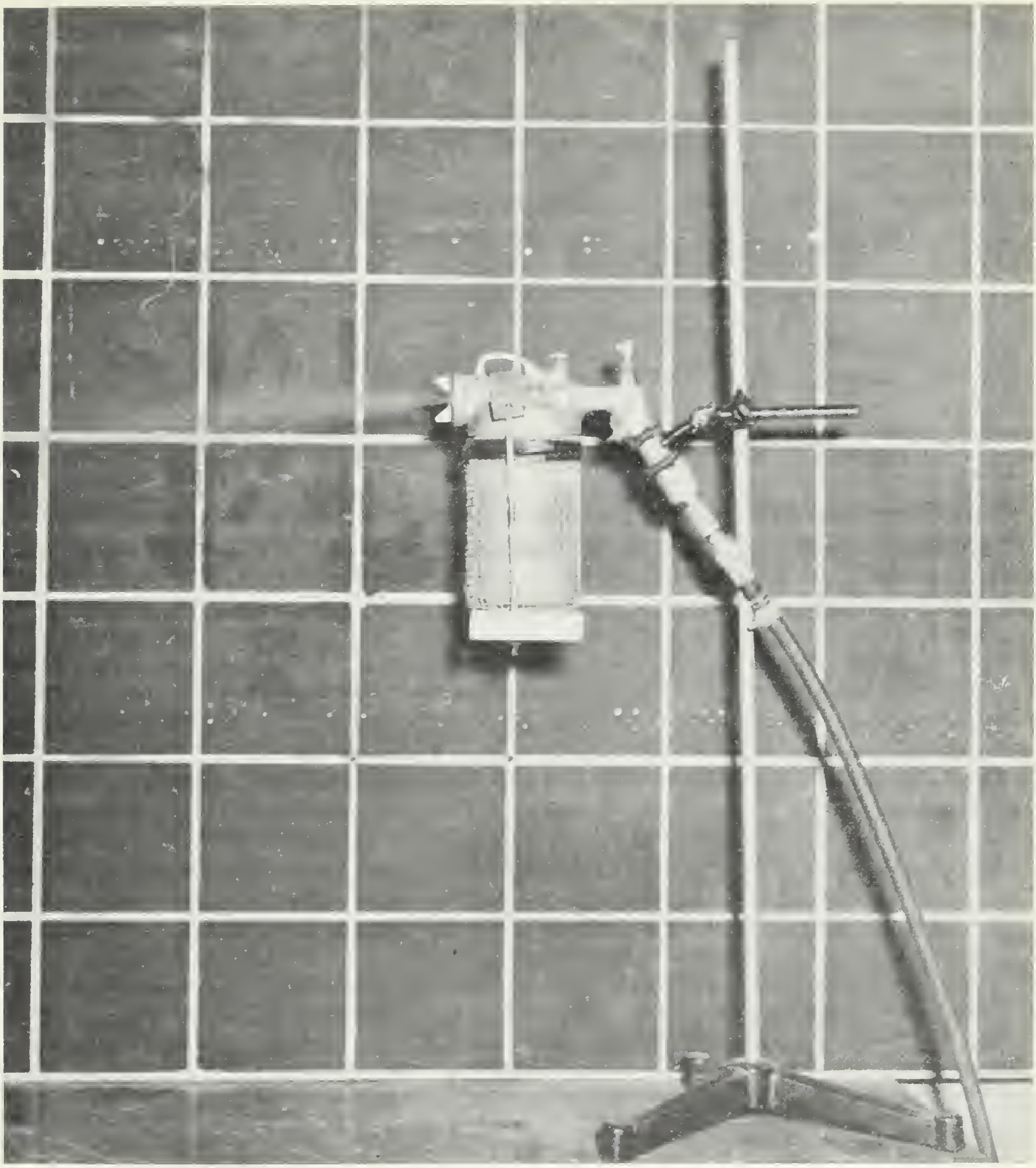

Figure 7.--Fallout disperser in operation.

Since the flock gun was to be used in a 6-foot wind tunnel, the maximum height above ground at which it could be mounted was about 5-1/2 feet. Fired under standard conditions from this height, the gun gave a pattern that was roughly 2 to 3 feet wide and about 10 feet long. The lengthwise distribution of material in this pattern was log normal. Thus, the characteristic parameters of the distribution patterns which could be measured with fair consistency were the positions of the logarithmic mean, the variance, and the peak in the distribution curve.

A desirable characteristic of a satisfactory fallout disperser is that it not influence the results of the wind tunnel experiment to be performed. This means that the dispersive effects of the flock gun should dissipate rapidly and the cloud of fallout should be falling vertically, free from the influence of the gun, well before it hits the ground. As a check, a series of experiments were performed in still air with the various particle sizes and with the gun mounted at distances from 9 inches to 5-1/2 feet above a table top. Cross-pattern strips of paper 3 inches wide were mounted on the top of the table, and samples were collected from these strips and weighed. The cumulative weights were plotted on log probability paper and the position of the pattern peak then plotted against height of disperser above table top.

The gun effect dissipated quite rapidly and particles were essentially in free-fall after they had fallen only a foot or so (fig. 8). Even more favorable results would be expected under conditions of horizontal wind since upon leaving the gun the particle velocity would need decrease only to the wind velocity through the tunnel and not to zero velocity as it must in still air.

HEAT SOURCE

These experiments required a heat source that would produce a convection column 2 or 3 feet across with updraft velocities of the order of several miles per hour. Also, the flames had to be readily lighted and extinguished to minimize delays between experiments. Gas flames meet this latter requirement ideally. Since cylinders of propane gas were readily available at the wind tunnel site, this gas was chosen as the fuel for all fire experiments. The heat source consisted of a group of four National Welding Equipment Company ribbon flame burners. Each had a burning area 3/4 inch by 12 inches, and the burning surface was located 9-1/2 inches above the floor. The original plan was to conduct the experiments with two rows of burners positioned with their axes at right angles to the wind tunnel. However, it was found that in this position the stronger winds readily extinguished the flames. Consequently, the basic configuration consisted of two rows of burners with axes parallel to the axis of the tunnel and positioned as close together as the burner bases would allow, about 10 inches between burners (fig. 9).

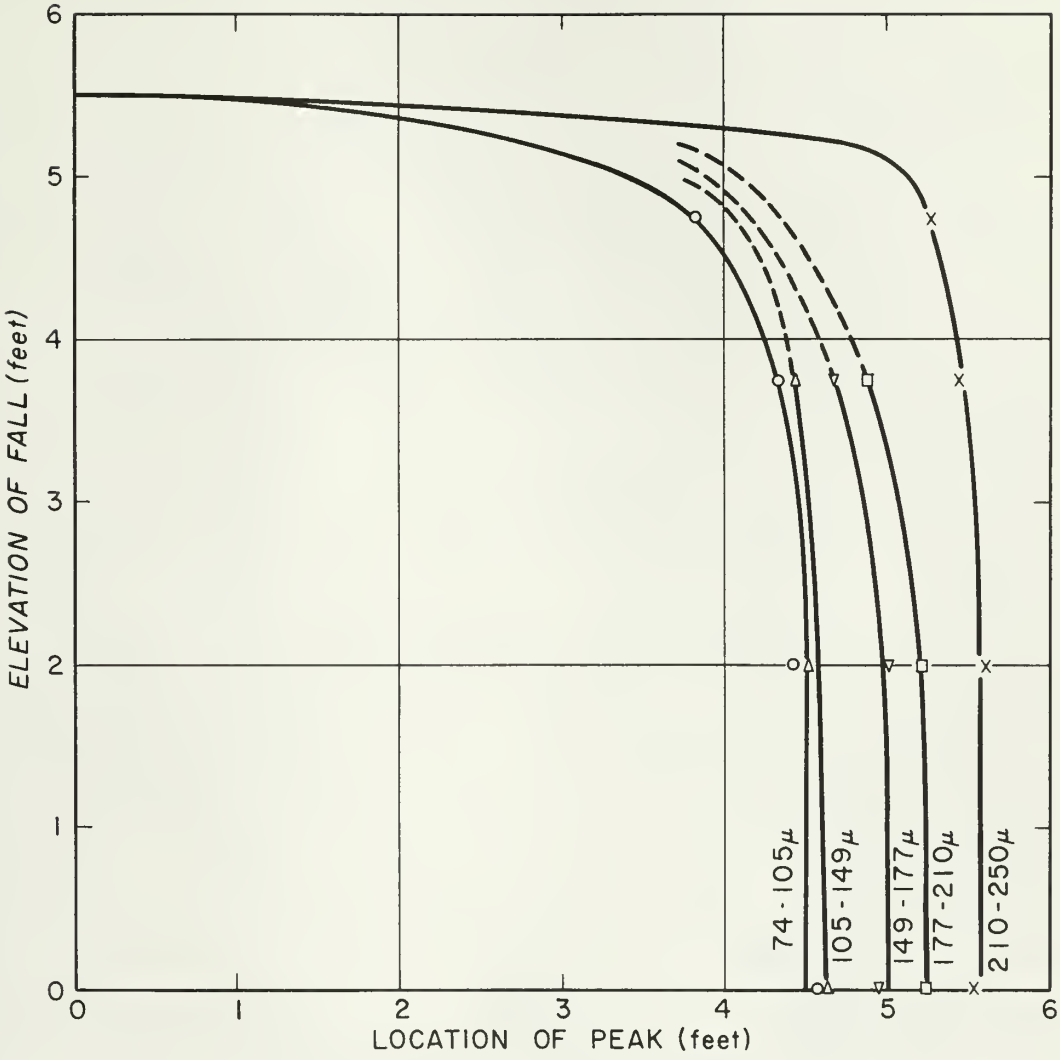

Figure 8.--Particle trajectory when fired from fallout disperser into still air.

Figure 9.--Two pairs of ribbon burners in parallel configuration.

Propane gas leaving the cylinder was passed through a Flamo pressure regulator which held the output pressure at 4 p.s.i. The gas was then fed through 1/2-inch inside diameter rubber hose to the burners. A flowmeter placed in the gas line gave the flow rate of gas as 1.78 cubic feet per minute. Assuming complete combustion, this corresponded to a heat output of 4,500 B.T.U. per minute. Although the burners had facilities for premixing of the gas with compressed air, no such premixing was used since more satisfactory characteristics of the convection column were obtained under free-burning conditions.

Under the conditions of use the gas burned with a yellow flame about 2 feet long. The parallel flames from the two sets of burners seemed to blend into one large flame and a single convection column. However, as a check against a possible valley in the center of the column, some experiments were performed with the front burners tilted toward each other in the shape of a "V" pointing in the direction in which the wind was blowing (fig. 10).

Under both configurations the cross-sectional area of the flames was approximately 2 square feet. For this area the heat output of the burners corresponded to the burning of wood fuels at the rate of approximately 6 tons per acre per minute.

Preliminary estimates were made of the updraft velocities of the convection columns in the wind tunnel with a wind velocity of 6 miles per hour. Measurements made with a Byram vane anemometer held with its axis in a vertical position at a point 8 feet downstream from the burners and 4-1/2 feet above the tunnel floor indicated an updraft velocity of about 2.2 miles per hour. This measurement is confirmed roughly also by the angle the flame made with the horizontal wind stream and by anemometer measurements taken at this angle. Unfortunately no instrumentation is available to permit accurate measurement of wind velocities in hot convection columns. Further work is being done to develop an instrument for measuring these velocities more accurately.

WIND TUNNEL EXPERIMENTS

Description of Tunnel

The wind tunnel experiments were conducted in a low-velocity Eiffel-type tunnel located outdoors at the San Dimas Experimental Forest in southern California (fig. 11). The tunnel, described in detail by Fons (1940) is 52 feet long and is composed of three main segments. The bellmouth entrance is 5 feet long, converging from 11-1/2 feet square to 6 feet square. The test section is 6 feet square and 32 feet long (an 8-foot extension of the test section was introduced since its description by Fons). To help insure parallel flow of air in the test section, a honeycomb is placed at the test section entrance. The exit consists of a converging section, a honeycomb and screen, and a diverging section. A four-bladed propeller-type fan, 4 feet in diameter, is located at the exit of the diverging section. The fan is belt-driven by a six-cylinder automobile engine, with a tachometer mounted on the propeller shaft to determine the fan speed.

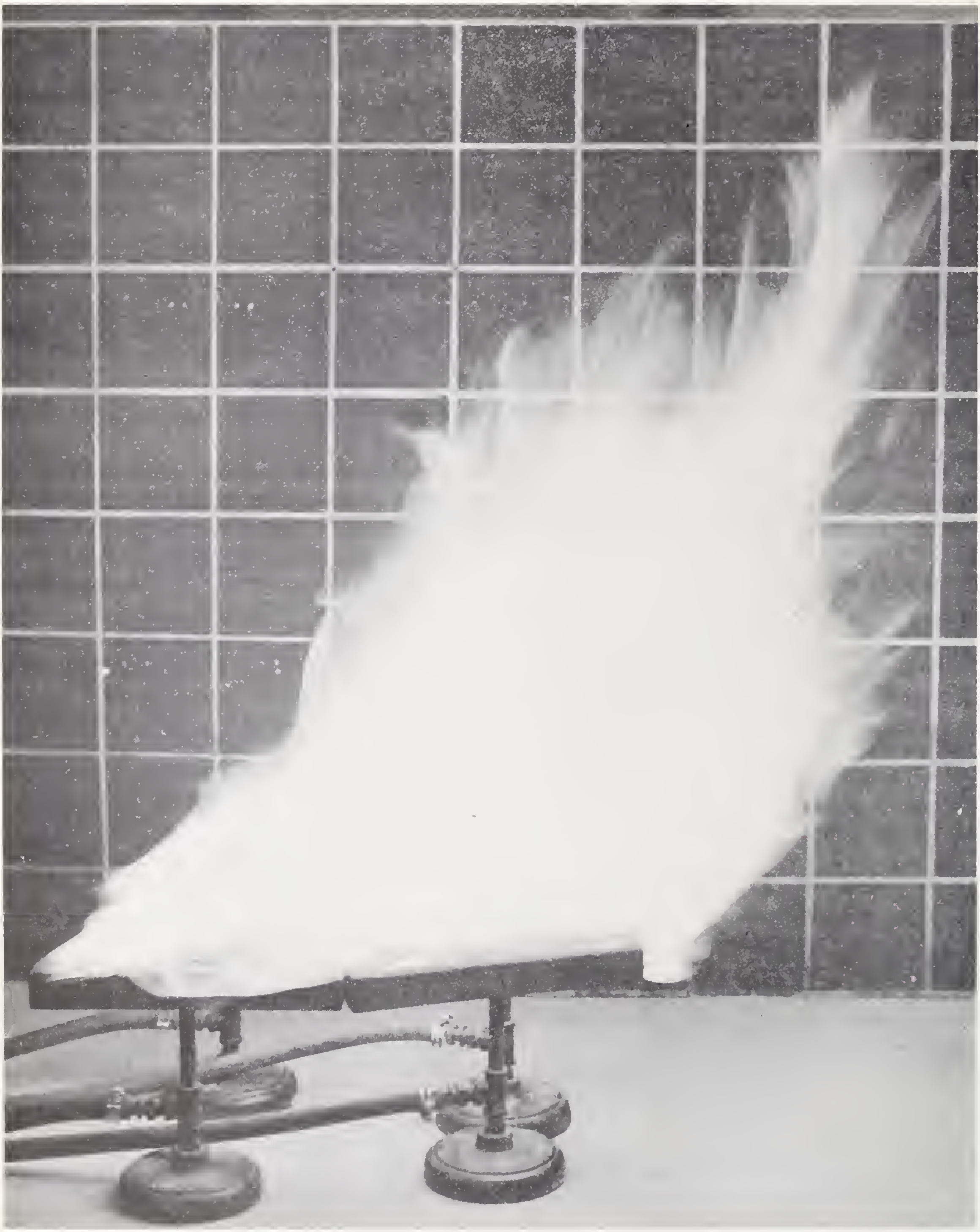

Figure 10.--"V" configuration of gas burners.

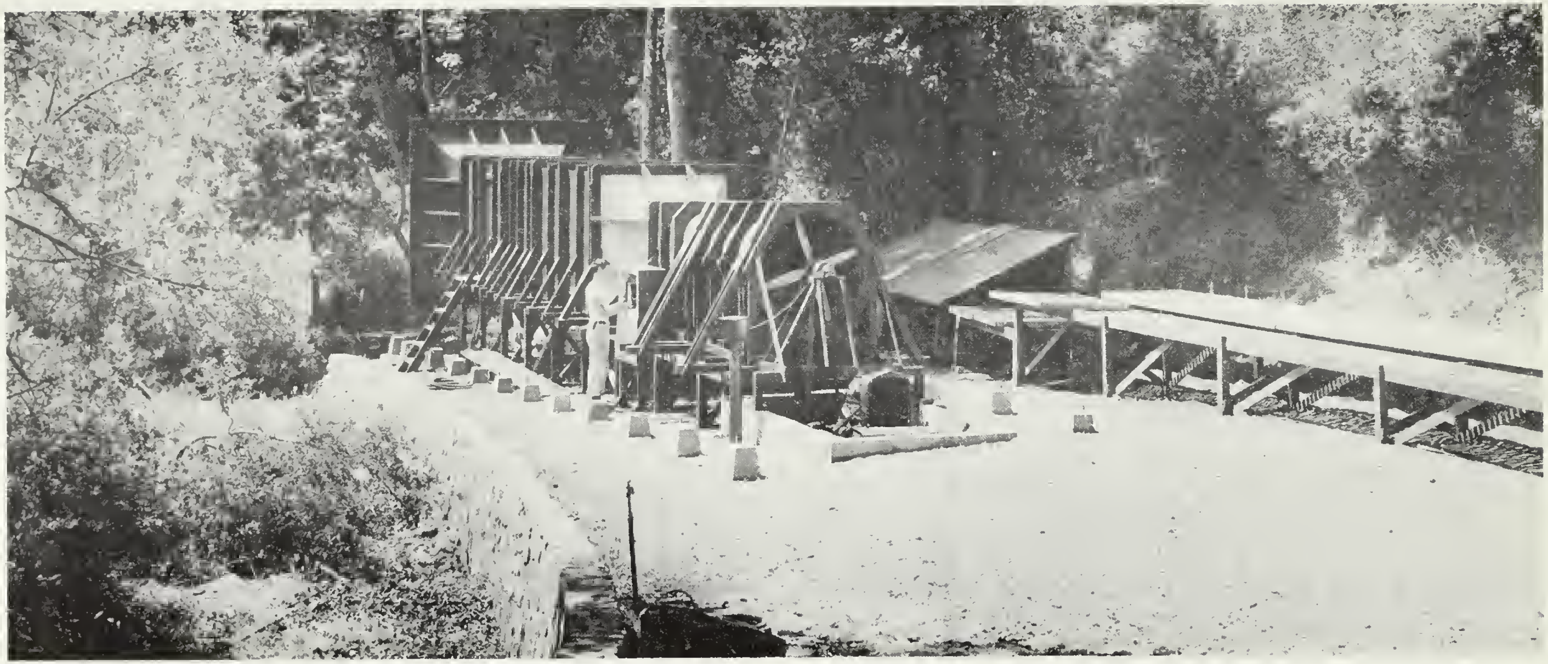

Figure 11.--Eiffel type low velocity wind tunnel used in the experiments.

Before these experiments the wind tunnel had last been used in the spring of 1945. Despite its exposure to the elements and minimal maintenance, all of the equipment, including the automobile engine used to drive the fan, was still in operating condition. A limited number of calibration checks of wind speed versus propeller speed in the 2- to 6-mile per hour range indicated that previous calibrations could be applied without correction. In fact, only two difficulties were encountered in the operation of the tunnel. When velocities above 6 miles per hour were introduced, some deteriorating plywood sections of the tunnel began to disintegrate. At lower rates, naturally occurring winds introduced significant deviations to the wind flows in the tunnel. This latter effect could be minimized by operating at night when the air was relatively calm.

The first inspection of the wind tunnel for use in these experiments was undertaken in the summer of 1957. A preliminary visit was planned to check on the conditions of the equipment and on the feasibility of using the fallout disperser and burners in the tunnel. Because of the excellent condition in which the tunnel was found, sufficient time was available to proceed with a number of extemporaneous experiments. Although more careful planning would have simplified subsequent analysis of the data, it turned out that the results of these preliminary experiments were sufficient to essentially exhaust the conclusions that could be reached with the apparatus available. Thus, no further trips to the wind tunnel were necessary.

Experimental Procedures

For the experimental determination of the influence of fire-induced convection column on fallout patterns, the flock gun was mounted at the entrance to the test section of the wind tunnel, centered horizontally, and 6 inches below the tunnel ceiling. The burners were positioned at varying distances ranging from 3-1/2 feet to 11 feet downwind of the flock gun. The floor of the tunnel was covered by a sheet of glossy black paper 30 inches wide (preliminary investigation indicated that the fallout showed up much better against the black background than against a white background). Filter paper collectors 6 inches in diameter were then mounted by thumbtack along the center of the black paper (and center of the wind tunnel) at 1- or 2-foot intervals. Additional collectors were mounted centered 10 inches to the right and left of the central row.

The experiment then consisted of adjusting the wind tunnel velocity to 2, 4, or 6 miles per hour, firing the flock gun containing one of the five size fractions of fallout, and determining the resultant pattern by weighing the material collected on the filter paper collectors to the nearest milligram (samples collected ranged from 2 or 3 grams down to less than a milligram). The burners, set in one of the two configurations and at one of four distances down the tunnel, were then ignited and the experiment repeated with a convection column formed. Observation through several of the optical ports in the walls of the tunnel confirmed the fact that the fallout cloud descended until it reached the convection column, then rose

sharply and finally descended, dispersed over a larger area further downwind. Typical patterns observed following runs without and with fire are shown in figure 12. A limited number of experiments were performed with a single Meeker burner producing a much smaller flame. The resultant change in pattern covered too small an area for detection with the gross measurements made in these experiments. However, the effect of this small burner is illustrated in the pattern shown in figure 13.

DISCUSSION

SELECTION OF CHARACTERIZING PARAMETERS

Fallout distribution patterns are three-dimensional. For the wind tunnel experiments, a downwind and crosswind dimension serves to identify a point within the pattern, and the amount of material landing at this point is given by the weight of sample collected. For the comparison of patterns produced in a large number of experiments, a point-by-point analysis, however, is not feasible. Instead, each pattern must be characterized in terms of a limited number of pertinent parameters and these parameters then compared as the experimental conditions are changed. For purposes of this study, for example, the characterizing parameters can be compared in the presence and absence of fire, all other factors being held constant.

Although the convection columns introduced both a longitudinal (downwind) and transverse (crosswind) dispersion, it was felt that the patterns could be sufficiently characterized by a two-dimensional measurement. Thus, downwind displacement could be identified by downwind measurements, and additional crosswind dispersion could be recognized by a decrease in the total amount in a downwind slice through the pattern. It was decided, therefore, to attempt to characterize the fallout patterns in terms of the measurements made on the central slice taken longitudinally down the tunnel. Attempts to fit this downwind distribution in terms of polynomial expressions through cubic proved unsuccessful. The data fit a quadratic expression nicely in the logarithm of the amount deposited. However, a least squares method of curve fitting (using the logarithms) was most unsatisfactory; such a procedure weighted the errors in measurements of the very small samples at the tails of the curve equally with the errors in the much more accurate measurements made on the large samples near the peak.

The excellent fit to a quadratic in logarithms led to the establishment of the characteristic log normal distribution to identify a particular pattern. That is, it was found that the weights taken in the central slice fit very nicely the expression[2/]

$$y = \frac{.4343(\Sigma y)(\Delta x)}{\sqrt{2\pi}\,(\sigma)(x)}\, e^{-\frac{(\log x - \log \mu)^2}{2\sigma^2}} \qquad (4)$$

[2/] This expression can be transformed simply into the form $\log y = a + b\,(\log x) + c\,(\log x)^2$.

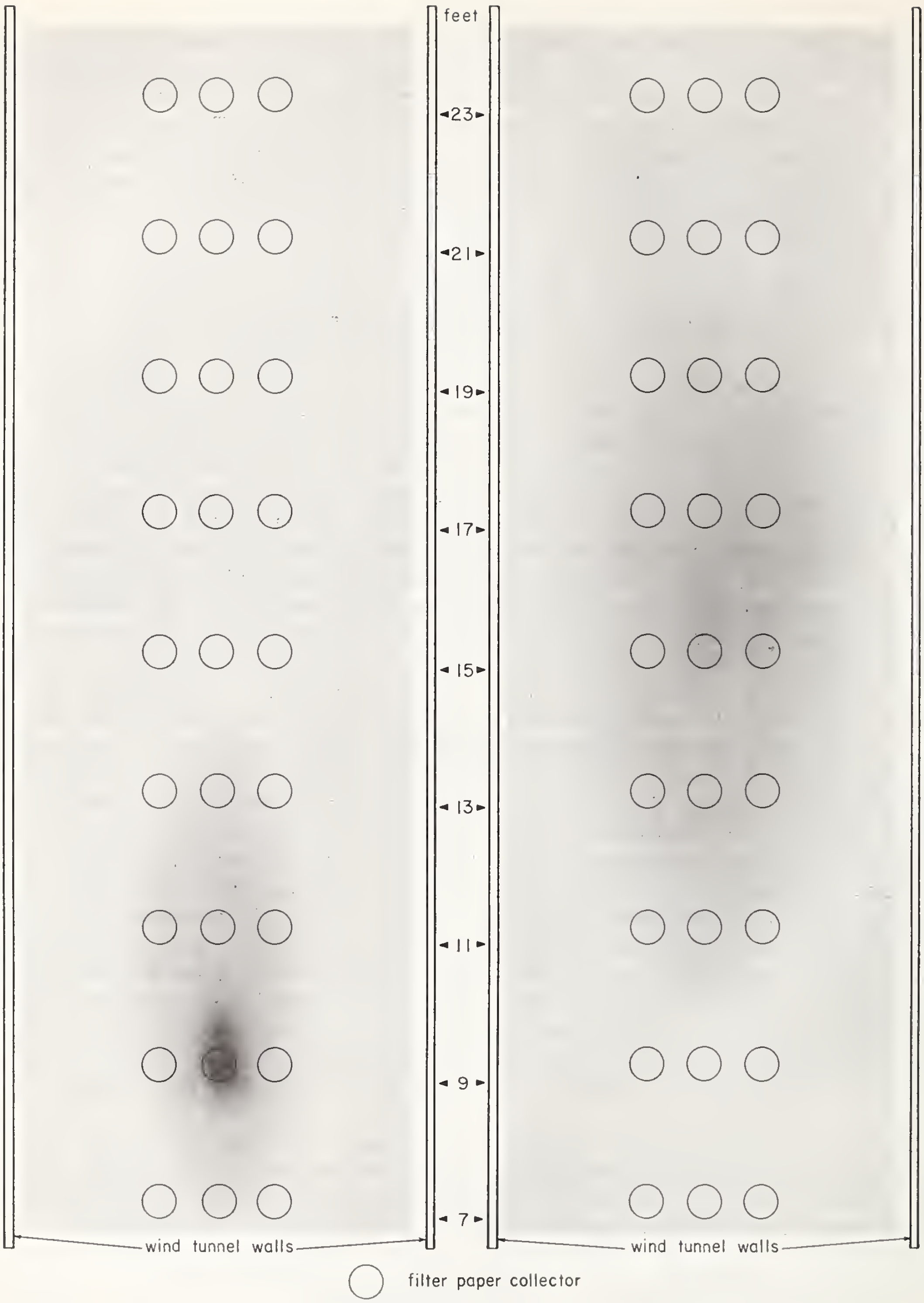

Figure 12.--Fallout patterns with and without fire. Particle size, 105-149 μ, wind velocity 2 m.p.h. Left Run No. 25, without fire; right, Run No. 26, with fire.

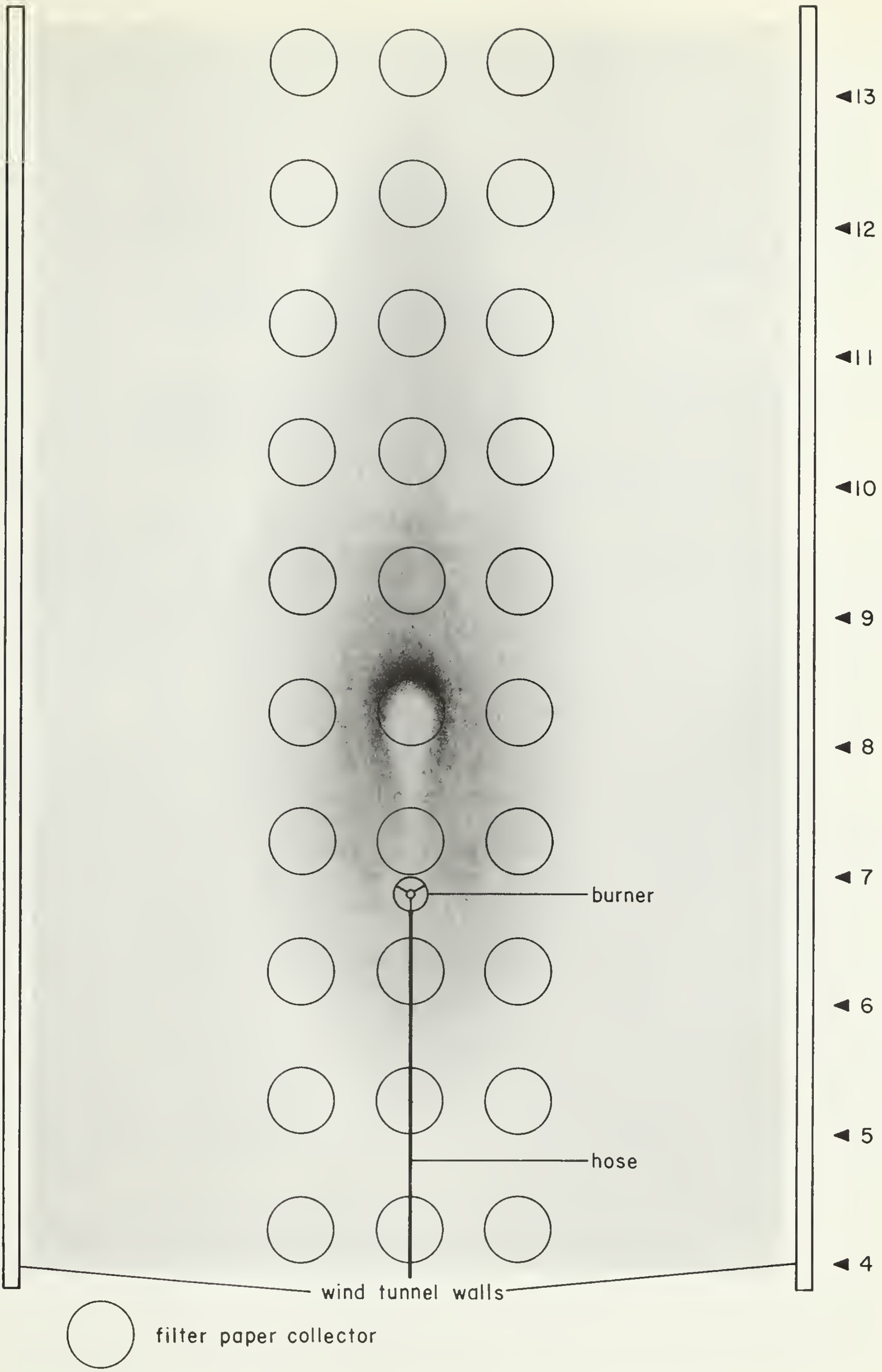

Figure 13.--Fallout pattern with fire when heat source is a small burner.

in which y is the weight of the material at any point in this downwind slice; Σy, the total weight of the samples in the slice; x, the downwind distance; and Δx, the class interval (the distance between points of measurement). The characterizing parameters, then, could be μ, the logarithmic mean distance, and σ, the standard deviation of this distance, and Σy, the total amount of material in the slice. Alternative parameters whose concepts are more readily grasped would be x_p, the distance to the peak in the parameter curve, which is related to μ and σ by the expression

$$\log x_p = \log \mu - 2.3026\sigma^2 \tag{5}$$

and y_p, the amount of material at the peak, which can be simply derived from equations 4 and 5 as

$$y_p = \frac{.1733(\Sigma y)(\Delta x)}{(\sigma)(x_p)} e^{-2.651\sigma^2} \tag{6}$$

Thus, the downwind displacement of the peak fallout concentration by fire can be seen directly by comparison of the values of x_p. The reduction in amount at the peak can be seen by comparison of the values of y_p. Of this reduction, the amount resulting from downwind dispersion can be seen from the value of σ, the remainder being due to crosswind dispersion.

SAMPLE ANALYSIS

The analytical procedure used in establishing the characteristic parameters for an individual run has considerable applicability in many other problems and will be described in detail in a subsequent report. As applied to these experiments the procedure can be illustrated briefly considering one of the more than a hundred experiments performed. The first two columns of table 2 present the basic measurements made for experiment number 108. Column 1 gives the sample distance in feet, that is, the distance between the fallout disperser and the midpoint of the fallout collector mounted in the central slice through the tunnel. Column 2 gives the weight of fallout collected in grams. For most runs samples were taken at 2-foot intervals. In this experiment, to more clearly establish the position of the peak, additional samples were taken at 1-foot intervals for part of the distance. The weights given in parenthesis in Column 2 represent values at points at which measurements were not made.

To establish the characterizing parameters for this run, a curve of y vs. x could be fitted to the data given in Columns 1 and 2 of table 2. Since such a curve is far from linear, graphical curve fitting would be subject to considerable error, particularly in establishing the position of the peak. However, the integral of a log normal curve may be plotted as a straight line on log probability paper. By making

Table 2.--Analysis of typical experiment

Sample distance x	Sample weight y	Upper class limit (Δx = 2 ft.)	Cum. weight	Cum. weight	Upper class limit (Δx = 1 ft.)	Cum. weight	Cum. weight	Corrected cum. weight	Corrected cum. weight
Ft.	Gm.	Ft.	Gm.	%	Ft.	Gm.	%	Gm.	%
					< 7.75			0.010	0.24
8.25	0.023				8.75	0.023	0.56	0.033	0.79
9.25	0.131	10.25	0.131	6.47	9.75	0.154	3.76	0.164	3.94
10.25	0.348				10.75	0.502	12.24	0.512	12.3
11.25	0.563	12.25	0.694	34.3	11.75	1.065	25.97	1.075	25.8
12.25	0.691				12.75	1.756	42.8	1.766	42.5
13.25	0.598	14.25	1.292	63.8	13.75	2.354	57.4	2.364	56.8
14.25	(0.550)				14.75	2.904	70.8	2.914	70.0
15.25	0.501	16.25	1.793	88.5	15.75	3.405	83.0	3.415	82.1
16.25	(0.348)				16.75	3.753	91.5	3.763	90.5
17.25	0.195	18.25	1.988	98.2	17.75	3.948	96.3	3.958	95.1
18.25	(0.116)				18.75	4.064	99.1	4.074	97.9
19.25	0.037	20.25	2.025	100.00	19.75	4.101	100.0	4.111	98.8
					> 19.75			4.160	100.0

Δx = 1 ft. (corrected):

$$\mu = 13.3$$

$$\sigma = \frac{\text{Log } 20.8 - \log 8.6}{5.152} = 0.0745$$

$$\log x_p = \log \mu - 2.3026\sigma^2 = 1.11107$$

$$x_p = 12.9$$

$$y_p = \frac{0.4343(\Sigma y)(\Delta x)}{\sqrt{2\pi}\,\sigma\, x_p}\, e^{\frac{-(\log x_p - \log \mu)^2}{2\sigma^2}} = 0.739$$

measurements at the center of a number of class intervals of equal size and plotting the cumulative values, expressed in percent, against the upper class limit of the interval, a straight line should result on log probability paper. Since measurements were not taken at equal class intervals, two alternatives are available. First, only measurements made at the 2-foot intervals could be used (the intervening 1-foot measurements being ignored), and the result obtained in this way is given in the next three columns, in which Column 3 gives the distance to the upper class limit, Column 4 the cumulative weight of these samples, and Column 5 this cumulative weight expressed as the percentage of the total weight of all of the samples. These values are plotted as the triangular points in figure 14.

An alternative procedure is to interpolate values for the 1-foot intervals at which measurements were not made and plot the data in terms of 1-foot class limits. The values given in parentheses in Column 2 represent linear interpolations between the adjoining points at which measurements were made. Column 6, then, gives the upper class limit assuming 1-foot intervals and Columns 7 and 8 the cumulative weight and cumulative percent for this case. These values are plotted as the square points in figure 15.

The points give an excellent straight line in the central portion of the graph, but turn off sharply at the limits (particularly the upper limit). This deviation from linearity is caused by the fact that a certain amount of material extends beyond the limits at which measurements were made (the sum of all the measured material being less than the total area under such a distribution curve). A correction may be made for this truncation by adding amounts for distances up to that at which the first measurement was made and beyond that at which the last measurement was made. This has been done in Columns 9 and 10 and, as may be seen, a straight line results throughout the entire range of measurements.

Although this correction for truncation is arbitrary, the curve plotted on log probability paper is an excellent indication of the correctness of the values chosen. In the example given, a correction of about 1 percent in the total weight was necessary to straighten out the ends of the curve. An overcorrection of the same amount would produce an equal curvature in the opposite direction. Thus, an iterative procedure can be used in making this correction, with the curve plotted after each iteration establishing whether an additional correction is required. The accuracy of establishing the correct curve is a function of the degree of truncation; however, it has been found that, as long as data are obtained on both sides of the peak, a remarkably narrow range of alternative curves will be permitted by the data. Even in the highly truncated cases where measurements are made on only one side of the peak (for example, in these experiments when most of the fallout extended beyond the limit of the test section of the wind tunnel) fairly close limits can be set upon alternative possibilities by considering such factors as the maximum range possible in values of the cumulative weight.

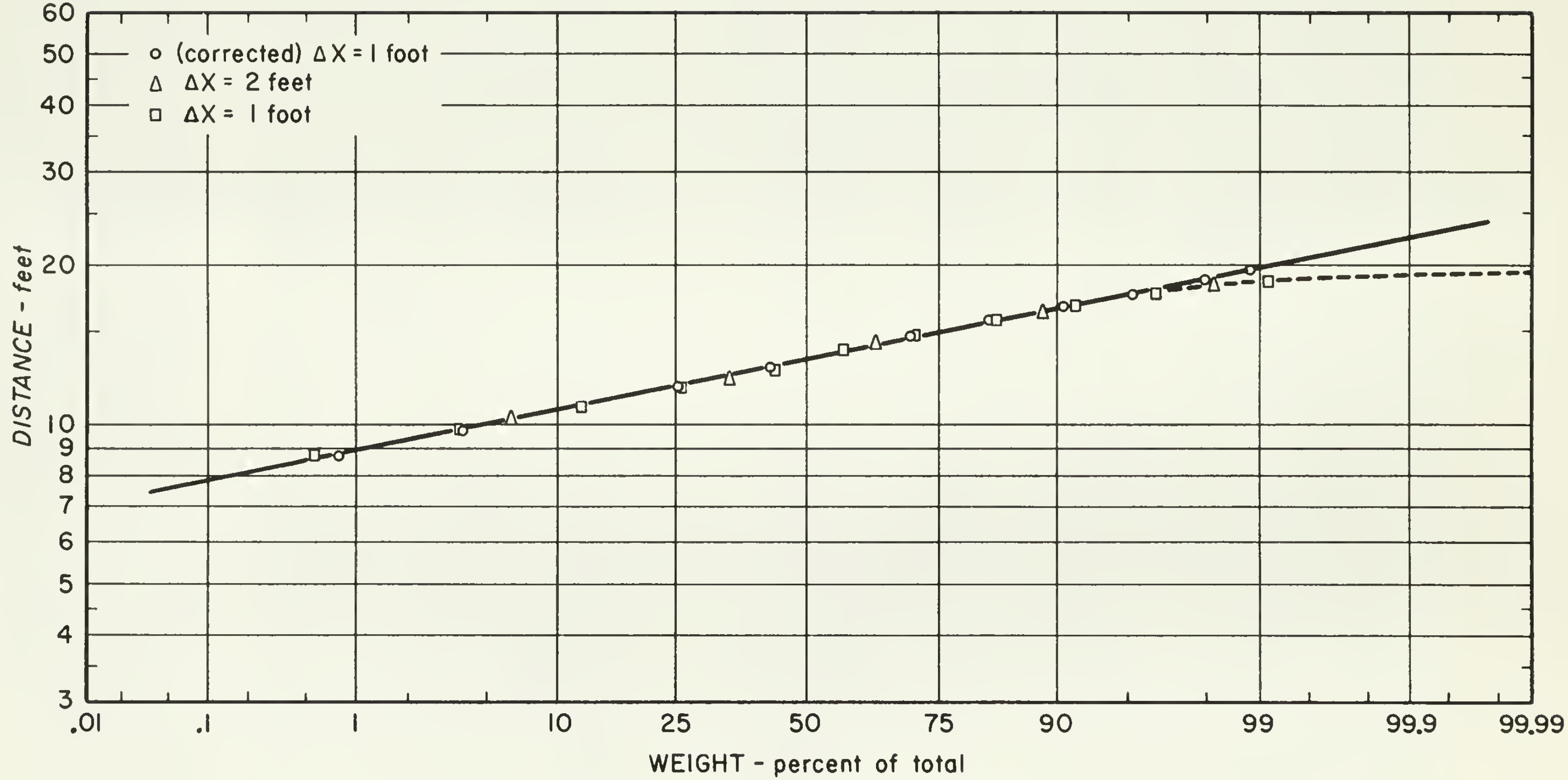

Figure 14.--Analysis of experimental run No. 108.

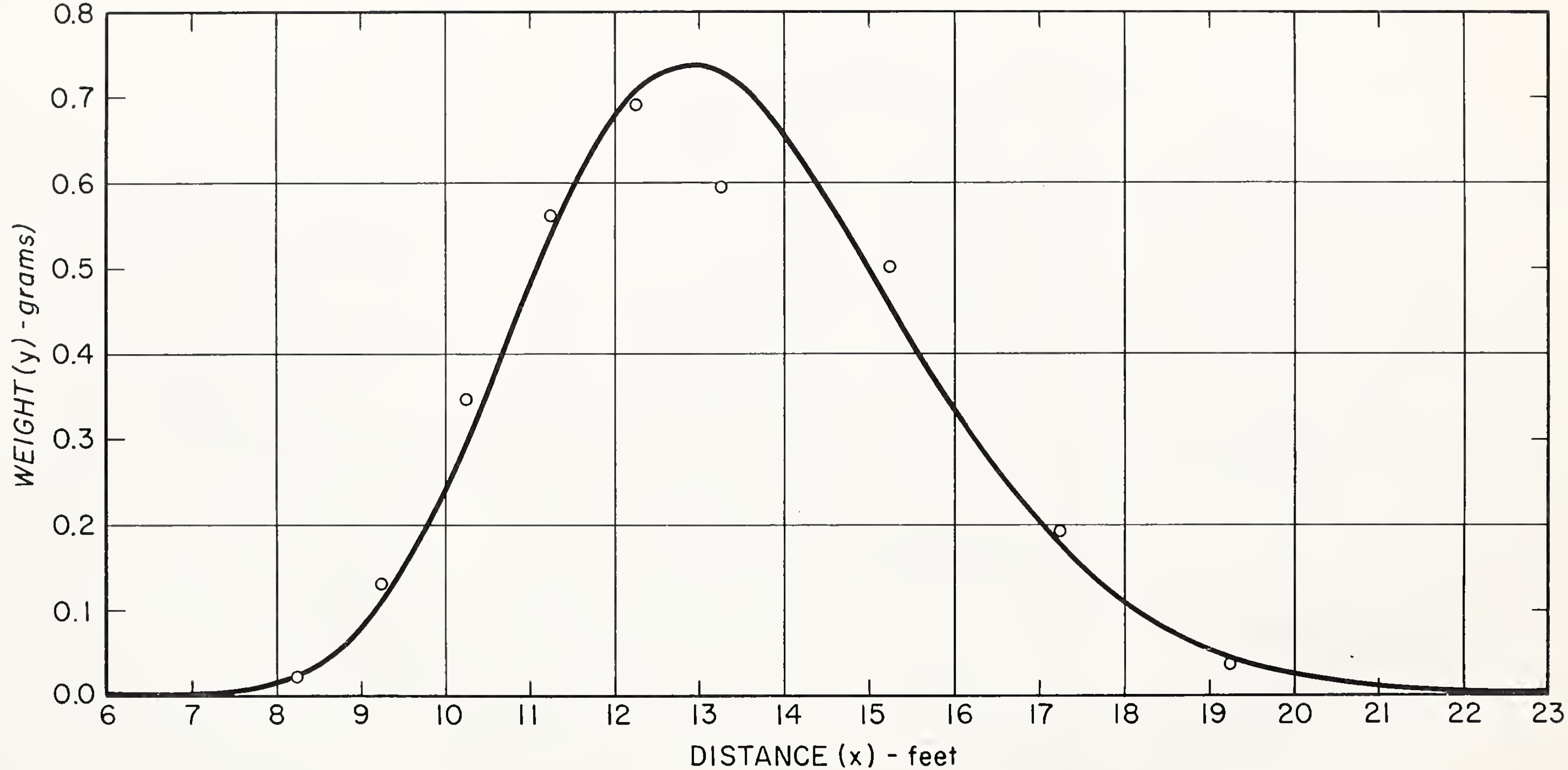

Figure 15.--Comparison of computed curve with experimental data.

Once the straight line given in figure 14 has been established, the characterizing parameters may be obtained as follows: The value of μ may be read directly as the value of the ordinate where the curve crosses the 50-percentile line. The value of σ is obtained from the slope of the curve. For example, since 99 percent of the material is found within the limits $\pm 2.576\sigma$ of the logarithmic mean, σ can be obtained by taking the difference between the logarithm of the ordinate as the curve crosses the 99.5 percent line and as the curve crosses the 0.5 percent line and dividing by 5.152. The position of the peak, then, can be obtained from the values of μ and σ using equation 5. It is interesting to note that in establishing the best straight line through the points, a line leading to a higher value of μ invariably has also a steeper slope. Thus, the value of x_p may be quite firmly established with larger errors in both μ and σ. Having established the value of σ and μ, a curve of y vs. x may be plotted directly from equation 4. Such a curve is given in figure 15, together with the original data shown in Columns 1 and 2 of table 2. It may be seen that the technique of obtaining the characteristic parameters from the integrated curve can smooth out rather sizeable point-to-point variations in the differentiated curve and permit the accurate establishment of the position of the peak when a freehand graphical fitting would be subject to considerable error. The value of y_p may, of course, be obtained from figure 15 or may be computed directly from equation 6.

EXPERIMENTAL RESULTS

The values of the characterizing parameters of all the experiments are presented in table 3. Inspection of these values shows the obvious effect of fire, of particle size, and of wind velocity. The lighter, slower-falling particles travelled farther down the tunnel before landing. The stronger the wind, the farther down the tunnel the particles went. In practically every case, the effect of the fire was to introduce a further lateral dispersion and downwind movement of the fallout, giving a more disperse, less concentrated pattern. The one obvious exception to this effect of fire occurred in the few experiments in which the burner was located at the edge of the no-fire pattern. In these cases air flow into the convection column shifted the peak of the pattern in an upwind direction.

Cursory inspection of the numbers in table 3 did not show whether there was any significant effect of burner position at the 3-1/2 and 7-foot positions or of burner configuration (in the parallel vs. V-shaped configurations). Consequently, a statistical analysis was undertaken to determine whether these factors introduced a significant effect. The experiment was considered to be a five-factor factorial. Eliminating all levels with insufficient replicates, the analysis was confined to two levels of each of four factors (burner position, burner configuration, wind, and fire condition) and four levels of the remaining factor (particle size). Owing to the extreme disproportionality of frequencies of

replicates, it was decided that a complete least-square solution should be attempted. Out of the possible 63 constants in an experiment such as this, the large number of cells without observations reduced the possible number of constants to 44. Again, owing to the way that observations were distributed among the possible factor combinations, models containing certain constants resulted in indeterminant solutions (singular matrices). Thus, no models were possible containing interactions involving burner condition, nor containing interactions greater than first order with burner configuration.

For the seven models that were admissible, multiple correlation coefficients were computed for x_p, μ, and σ, using the IBM 701 machine available at the University of California Computer Center. On the basis of these results (table 4), the model containing particle size, wind velocity, and fire condition alone (including interactions) was adopted. Thus, in obtaining average values of the characteristic parameters, the burner configuration and burner position (for those runs in which the burner was at 3-1/2 or 7 feet) were ignored.

The average values of the characteristic parameters were then obtained for a given fire, wind, and particle-size situation (table 5). Examination of the values of x_p and y_p in this summary table show clearly the effect of the fire-induced convection column in these experiments. In each case, fire resulted in a marked downwind displacement of the peak in the fallout distribution pattern (and thus of the whole pattern) with a decrease in value at the peak ranging up to a factor of 10. How this effect was influenced by the walls and ceiling of the wind tunnel is not clear. Consequently, these results are not directly extrapolatible to free-air conditions.

One final measurement bearing upon the interpretation of these experimental runs is worthy of mention. Part of the downwind distribution of fallout in any run may be attributed to further fractionation of the particles within the particular sieve size fraction on the basis of fall velocity. Consequently, for a number of runs samples were collected on transparent gummed paper mounted along the centers of the tunnel. Representative samples were then measured under the microscope using the statistical technique described previously. The results, as would be expected, show a definite fractionation down the tunnel, with mean particle size decreasing with increasing distance downwind (table 5).

Table 3.--Characterizing parameters for wind tunnel fallout patterns

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
74-105	No fire	2	3.5	37	2.42	10.0	0.080	9.7	1.07
			3.5	50	5.42	9.2	.095	8.8	2.21
			3.5	63	2.50	9.9	.087	9.5	1.02
			7	85	2.33	10.3	.059	10.1	1.34
			7V	87	2.18	12.5	.058	12.3	1.04
			X	81	2.98	11.3	.058	11.1	1.58
			X	83	2.44	10.7	.066	10.4	1.20
			Mean values		2.90	10.6	0.072	10.3	1.35
	With fire	2	3.5	38	1.00	19.0	0.138	17.1	0.139
			3.5	51	0.85	16.8	.079	16.2	.222
			3.5V	64	0.47	16.8	.071	16.3	.134
			7	86	1.00	29.0	.140	26.1	.112
			7V	88	1.22	18.7	.172	15.7	.131
			X	84	(2.08)	(12.2)	(.075)	(11.8)	(.799)
			X	82	(2.26)	(11.1)	(.079)	(10.7)	(.921)
			Mean values		0.91	20.1	0.120	18.3	0.148
	No fire	4	3.5	17	1.70	19.5	0.072	19.0	0.423
			3.5	23	0.89	21.0	.060	20.6	.247
			3.5	94	1.37	22.1	.082	21.3	.267
			7	89	1.85	19.6	.077	19.0	.434
			7V	91	1.45	19.3	.090	18.5	.294
			11	20	1.70	21.9	.079	21.2	.502
			11	21	1.85	21.8	.059	21.4	.308
			11	93	1.47	21.1	.080	20.4	.306
			Mean values		1.54	20.8	0.075	20.2	0.348

1/ Numbers: distance in feet between fallout disperser and burner; V designates V-shaped burner configuration; X designates Meeker burner.

Table 3--Continued

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
74-105	With fire	4	3.5	18	0.260	27.5	0.076	26.7	0.048
			3.5	24	.133	22.0	.071	21.3	.030
			7	90	.640	29.5	.158	25.0	.039
			7V	92	.620	23.7	.144	21.2	.066
			11	19	(.260)	(18.8)	(.099)	(17.9)	(.048)
			11	22	(.190)	(25.4)	(.083)	(24.5)	(.032)
			Mean values		0.413	25.7	0.112	23.6	0.046
105-149	No fire	2	3.5	9	1.90	9.4	0.092	9.0	0.78
			3.5	15	3.01	9.2	.044	9.1	2.60
			3.5	109	3.55	9.1	.046	9.0	2.96
			3.5	25	2.74	9.9	.047	9.8	2.05
			7	104	4.50	8.2	.056	8.1	3.41
			7	106	5.00	8.5	.053	8.4	3.89
			Mean values		3.45	9.0	0.056	8.9	2.62
	With fire		3.5	10	0.68	19.9	0.118	18.5	0.104
			3.5	16	1.08	15.2	.068	14.8	.367
			3.5	26	0.92	16.0	.073	15.6	.277
			3.5	110	1.12	16.8	.078	16.3	.302
			3.5V	108	2.08	13.3	.074	12.9	.739
			3.5V	111	0.62	14.3	.087	13.7	.176
			7	105	1.80	13.2	.086	12.7	.561
			7	107	3.39	12.5	.109	11.7	.892
			Mean values		1.46	15.2	0.087	14.5	0.427

1/ Numbers: distance in feet between fallout disperser and burner; V designates V-shaped burner configuration; X designates Meeker burner.

Table 3--Continued

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
105-149	No fire	4	3.5	3	1.96	15.8	0.077	15.3	0.57
			3.5	6	1.83	15.4	.072	15.0	0.58
			3.5	7	1.64	15.8	.067	15.4	0.54
			3.5V	43	1.92	15.1	.077	14.0	0.61
			7	95	3.09	15.5	.070	15.1	1.00
			7	97	1.89	15.3	.075	14.8	0.58
			9	1	0.91	17.3	.064	17.0	0.29
			11	45	2.12	16.2	.061	15.9	0.75
			11	56	3.20	13.2	.083	12.7	1.03
			11	99	2.60	14.9	.069	14.5	0.73
			Mean values		2.12	15.4	0.072	15.0	0.67
	With fire	4	3.5	4	0.65	21.2	0.098	20.2	0.110
			3.5	5	0.60	21.3	.094	20.1	.108
			3.5	8	0.62	22.6	.097	21.5	.100
			3.5	12	0.68	21.0	.102	19.9	.113
			3.5	14	0.46	20.9	.110	19.6	.073
			3.5V	44	0.55	22.8	.087	21.9	.098
			3.5V	102	0.85	18.5	.076	17.9	.021
			3.5V	103	1.80	18.9	.078	18.4	.425
			7	96	1.25	20.3	.077	19.7	.281
			7	98	0.60	21.6	.081	20.9	.121
			9	2	(0.93)	(17.3)	(.064)	(16.9)	(.206)
			11	46	(1.60)	(14.9)	(.131)	(13.6)	(.298)
			11	57	(1.70)	(14.2)	(.154)	(12.5)	(.288)
			11	100	(2.50)	(13.8)	(.147)	(12.3)	(.453)
			11V	47	(1.24)	(17.3)	(.091)	(16.6)	(.280)
			11V	58	(3.42)	(16.8)	(.087)	(16.1)	(.829)
			11V	101	(2.82)	(16.9)	(.086)	(16.2)	(.685)
			Mean values		0.81	20.9	0.090	20.0	0.145

1/ Numbers: distance in feet between fallout disperser and burner; V designates V-shaped burner configuration; X designates Meeker burner.

Table 3--Continued

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
105-149	No fire	6	3.5	52	0.92	23.2	0.064	22.7	0.221
			3.5	54	0.31	23.5	.076	22.9	.089
			Mean values		0.62	23.4	0.070	22.8	0.155
	With fire	6	3.5	53	(0.5)	(31)	(0.085)	(29.8)	(0.067)
			3.5	55	(0.5)	(35)	(.104)	(33.1)	(.049)
			Mean values		(0.5)	(33)	(0.094)	(31.4)	(0.058)
149-177	No fire	2	3.5	73	4.15	8.1	0.033	8.05	5.35
			3.5V	75	3.09	8.1	.033	8.05	4.03
			X	78	3.84	8.6	.041	8.53	3.79
			X	80	3.27	8.3	.041	8.23	3.35
			Mean values		3.59	8.3	0.037	8.22	4.13
	With fire	2	3.5	74	1.37	12.1	0.069	11.8	0.57
			3.5V	76	1.18	12.0	.058	11.8	.59
			X	77	(3.36)	(8.6)	(.065)	(8.4)	(2.09)
			X	79	(3.18)	(8.7)	(.060)	(8.5)	(2.14)
			Mean values		1.28	12.0	0.064	11.8	0.58
	No fire	4	3.5	27	2.16	12.9	0.044	12.8	1.34
			3.5	29	1.58	14.5	.050	14.3	0.76
			3.5	65	1.63	13.9	.042	13.8	0.97
			7	67	1.86	13.5	.035	13.4	1.38
			Mean values		1.81	13.7	0.043	13.6	1.11

1/ Numbers: distance in feet between fallout disperser and burner; V designated V-shaped burner configuration; X designates Meeker burner.

Table 3--Continued

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
149-177	With fire	4	3.5	28	1.02	17.5	0.090	16.8	0.230
			3.5	30	1.06	17.9	.082	17.3	.256
			3.5	66	0.96	18.5	.079	17.9	.230
			7	68	0.88	16.5	.087	15.8	.217
			Mean values		0.98	17.6	0.085	17.0	0.233
	No fire	6	3.5	69	6.00	14.9	0.069	14.5	2.04
			3.5	71	6.00	15.3	.064	15.1	2.11
			Mean values		6.00	15.1	0.066	14.8	2.08
	With fire	6	3.5	70	0.64	22.5	0.094	21.5	0.107
			3.5	72	1.60	23.0	.078	22.3	.307
			Mean values		1.12	22.8	0.086	21.9	0.207
177-210	No fire	2	3.5	35	3.24	8.2	0.022	8.2	6.1
			3.5	48	2.75	7.5	.023	7.5	5.5
			Mean values		3.00	7.8	0.022	7.8	5.8
	With fire	2	3.5	36	2.18	11.8	0.062	11.6	1.04
			3.5	49	1.72	11.5	.068	11.2	0.77
			Mean values		1.95	11.6	0.065	11.4	0.90
210-250	No fire	2	3.5	59	0.99	7.8	0.024	7.7	1.77
			3.5	61	0.81	7.9	.030	7.8	1.20
			Mean values		0.90	7.8	0.027	7.8	1.44

1/ Numbers: distance in feet between fallout disperser and burner; V designates V-shaped burner configuration; X designates Meeker burner.

Table 3.--Continued

Particle size, microns	Fire cond.	Wind velocity	Burner config. 1/	Run No.	Corrected total weight	Log mean distance	Standard deviation	Peak position	Peak weight
		M.p.h.			Gm.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Gm.
210-250	With fire	2	3.5	60	0.58	9.2	0.044	9.1	0.49
			3.5	62	0.61	9.0	.044	8.9	.53
			Mean values		0.60	9.1	0.044	9.0	0.51
	No fire	4	3.5	31	2.08	11.3	0.032	11.2	1.99
			3.5	33	1.68	11.2	.037	11.1	1.42
			Mean values		1.88	11.2	0.034	11.2	1.71
	With fire	4	3.5	32	1.26	13.8	0.053	13.6	0.60
			3.5	34	1.13	13.9	.065	13.4	.39
			Mean values		1.20	13.8	0.059	13.5	0.50
	No fire	6	3.5	39	1.13	14.9	0.045	14.7	0.59
			3.5	41	0.96	15.1	.038	15.0	.58
			Mean values		1.04	15.0	0.042	14.8	0.58
	With fire	6	3.5	40	1.02	17.8	0.058	17.4	0.385
			3.5	42	0.98	17.6	.059	17.3	.330
			Mean values		1.00	17.7	0.058	17.4	0.358

1/ Numbers: distance in feet between fallout disperser and burner; V designates V-shaped burner configuration; X designates Meeker burner.

Table 4.--Multiple correlation coefficients for admissible models

Model	Number of variables	Multiple correlation coefficient for x_p	μ	σ
1st order, including:				
Fire, wind, particle size	6	90.0	89.0	77.3
Fire, wind, size, burner position	7	90.0	89.2	78.8
Fire, wind, size, burner configuration	7	90.4	89.3	77.3
Fire, wind, size, position, configuration	8	90.4	89.5	78.8
2nd order (1st order interactions):				
Fire, wind, particle size	13	92.5	91.7	80.1
Fire, wind, size, configuration	19	93.8	92.8	81.5
3rd order (2nd order interactions):				
Fire, wind, size	16	94.6	94.3	82.3

Table 5.--Average values of the characteristic parameters

Particle size range, microns	Mean velocity	Without fire				With fire			
	M.p.h.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Ft.	μ, Ft.	σ, Ft.	x_p, Ft.	y_p, Ft.
74-105	2	10.6	0.072	10.3	1.35	20.1	0.120	18.3	0.148
	4	20.8	0.075	20.2	0.348	25.7	0.112	23.6	0.046
105-149	2	9.0	0.056	8.9	2.62	15.2	0.087	14.5	0.427
	4	15.4	0.072	15.0	0.67	20.9	0.090	20.0	0.145
	6	23.4	0.070	22.8	0.155	(33)	(0.094)	(31.4)	(0.058)
149-177	2	8.3	0.037	8.2	4.13	12.0	0.064	11.8	0.58
	4	13.7	0.043	13.6	1.11	17.6	0.085	17.0	0.233
	6	15.1	0.066	14.8	2.08	22.8	0.086	21.9	0.207
177-210	2	7.8	0.022	7.8	5.8	11.6	0.065	11.4	0.90
210-250	2	7.8	0.027	7.8	1.44	9.1	0.044	9.0	0.51
	4	11.2	0.034	11.2	1.71	13.8	0.059	13.5	0.50
	6	15.0	0.042	14.8	0.59	17.7	0.058	17.4	0.358

Table 6.--Downwind fractionation of fallout samples

Nominal size range, microns	Condition	Run No.	Distance	Cumulative percent	Mean particle size	Standard deviation of sizes	Actual size range	Number of particles	Standard deviation of means
			Ft.		Microns	Microns	Microns		Microns
74-105	2 m.p.h., Fire	88	13	20	146	29	90-239	51	4
			15	32	133	30	81-220	62	3.9
			23	67	112	20	66-163	50	2.9
	2 m.p.h., No fire	87	9	1	124	28	69-245	104	2.7
			13	64	100	24	41-193	113	2.3
			17	99	98	25	26-155	101	2.5
105-149	2 m.p.h., No fire	25	7	< 1	137	43	63-281	100	4.3
			11	85	132	26	79-214	51	3.7
			15	> 99	113	32	55-175	100	3.2
	2 m.p.h., Fire	26	13	10	156	32	95-238	50	4.5
			15	40	149	24	99-219	52	3.3
			21	96	137	28	71-212	71	3.3
	4 m.p.h., No fire	95A	10	2	164	27	117-224	51	3.8
			16	66	145	25	98-201	53	3.4
			22	98	134	26	71-184	50	3.6
	4 m.p.h., Fire	96A	16	10	150	32	83-219	52	4.5
			23	75	154	32	84-219	50	4.6
105-149 (Fraction from new samples of NRDL fallout.)	2 m.p.h., No fire	109	8	10	147	24	97-222	50	3.4
			10	80	133	24	87-195	54	3.3
			12	99	130	23	65-175	50	3.3
	2 m.p.h., Fire	110	12	3	159	29	110-246	51	4.1
			17	50	146	21	95-193	54	2.8
			19	78	147	26	108-232	52	3.6

CONCLUSION

It has been shown that, under some conditions with sufficiently high updraft, a fire-induced convection column can have a marked effect upon radiological fallout patterns. The effect of the column itself will be markedly influenced by the air flow in and around the column. The experiments conducted in this study were performed in a wind tunnel in which this flow was influenced by the tunnel walls and ceiling. Consequently the results are not directly applicable to open-air conditions. However, the results do suggest quite strongly that a marked effect will be found for a large-scale fire burning freely. Under conditions of sizeable civil defense activity, such an effect could greatly alter the necessary civil defense planning and action. Consequently, open-air experiments on a larger scale should be performed in an attempt to establish the parameters affecting the fallout pattern in the presence of a fire in the event of a nuclear detonation where fallout occurs and combustible material is available.

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